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A STUDY OF PLASMA DECAY IN A TOROIDAL MAGNETIC FIELD

by

V. Ye. Golant, O. B. Danilov, and A. P. Zhilinskiy

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

A STUDY OF PLASMA DECAY IN
A TOROIDAL MAGNETIC FIELD

V. Ye. Golant, O. B. Danilov
and A. P. Zhilinskiy

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This article presents the results of a theoretical and experimental study of the decay of slightly ionized plasma in a toroidal chamber along which a magnetic field is directed. Equations for plasma decay have been derived from the theoretical study and their solution found and analyzed as a description of the spatial distribution of the plasma concentration and of the changes in its concentration over time. The change over time in the concentration of charged plasma particles undergoing decay within the helium-filled dielectric chamber was calculated experimentally for a variety of conditions. Experimental data on the effect of toroidal drift in the magnetic field on plasma decay agree with the theoretical conclusions.

Introduction

Most of the research in the area of plasma decay within a magnetic field is directed toward the end of obtaining data on charged particle diffusion. In one of their first experiments, Bostick and Levine [1] studied the decay of slightly ionized plasma within a metal toroidal chamber. This work contains their calculation of the decay time constant based on curves describing the change over time in the concentration of the charged plasma particles. The relationship of the decay constant, as it turns out, to the longitudinal magnetic field has a maximum, the value of the maximum decay constant increasing with the pressure of the gas. In the authors' view, the presence of this maximum provides evidence of an irregularity in the relationship of the coefficient of diffusion to the magnetic field as predicted by the theory.

Work [1], as well as many subsequently published articles, considers the experimental results referred to as proof of the occurrence of plasma instability as well as of an anomalous diffusion accompanying it. It should be pointed out, however, that this is a questionable interpretation of the experimental data, considering the fact that there had been no analysis of the effect on the plasma decay of the charged particle drift caused by the nonuniformity of the magnetic field (although the authors did refer to the possibility of a substantial effect of toroidal drift). The purpose of the present work has been precisely to study the effect on plasma decay of charged particle drift in a nonuniform magnetic field.

1. THE THEORY OF PLASMA DECAY IN A TOROIDAL MAGNETIC FIELD

a) The Decay Equation

Let us consider the decay of slightly ionized plasma in a toroidal chamber along which a magnetic field is directed (Figure 1). Within the cylindrical coordinate system, the field components are calculated in accordance with the equations

$$H_\varphi = H_0 \frac{R}{r}; \quad H_r = H_z = 0. \tag{1}$$

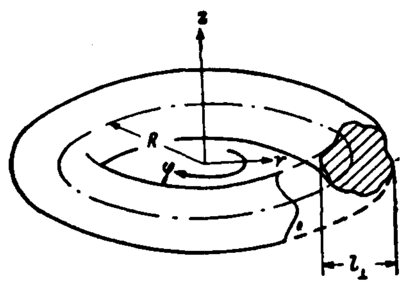

Figure 1

In the course of our discussion we will consider the radius of the chamber's curvature to be much greater than its transverse dimensions

$$R \gg l_\perp. \tag{2}$$

We calculate the change in concentration of charged particles during the process of plasma decay in accordance with the equation

$$\frac{\partial n_\alpha}{\partial t} + \nabla (n_\alpha \mathbf{u}_\alpha) = 0, \tag{3}$$

in which n_α - concentration, $\mathbf{u}_\alpha$ - average particle velocity;* we assume that the processes of the removal of charged particles en masse are immaterial. The condition of quasineutrality of a plasma

*Index $\alpha = e$ will indicate electron values; index $\alpha = i$ – the ion values.

consisting of electrons and singly-charged ions results in the equality of their concentrations

$$n_e = n_i = n, \tag{4}$$

and, correspondingly, to equality in the divergence of the flows

$$\nabla (n_e \mathbf{u}_e) = \nabla (n_i \mathbf{u}_i). \tag{5}$$

Average charged particle velocity may be calculated employing the averaged equation for particle motion, which, as we know, is a corollary of the kinetic equation

$$m_\alpha \frac{\partial \mathbf{u}_\alpha}{\partial t} + m_\alpha (\mathbf{u}_\alpha \nabla) \mathbf{u}_\alpha = Z_\alpha e \mathbf{E} + \\ + \frac{Z_\alpha e}{c} [\mathbf{u}_\alpha \times \mathbf{H}] - \frac{T_\alpha \nabla n_\alpha}{n_\alpha} - m_\alpha \nu_\alpha \mathbf{u}_\alpha. \tag{6}$$

Here m_α - mass; $Z_\alpha e$ - charge $(Z_i = 1,\ Z_e = -1)$; $\mathbf{E}$ - electrical field intensity; $\mathbf{H}$ - magnetic field intensity, T_α - temperature in energy units (temperature assumed to remain constant); ν_α - effective frequency of the collisions of α-type particles with neutral atoms (the frequency of the collisions of charged particles with neutral atoms in a slightly ionized gas is much greater than the frequency of the collisions of charged particles with one another).

Average particle velocity is usually much lower than thermal velocity $u_\alpha \ll \sqrt{\frac{T_\alpha}{m_\alpha}}$, and we may ignore the second, nonlinear term in equation (6). In the case of a sufficiently slow plasma decay, in which $\left|\frac{\partial}{\partial t}\right| \ll \nu_\alpha$, we may ignore the first term as well. Equation (6) takes the form

$$m_\alpha \nu_\alpha \mathbf{u}_\alpha - \frac{Z_\alpha e}{c} [\mathbf{u}_\alpha \times \mathbf{H}] = Z_\alpha e \mathbf{E} - T_\alpha \frac{\nabla n_\alpha}{n_\alpha}. \tag{7}$$

By solving the vector equation we obtain the following expressions for the transverse (perpendicular to the magnetic field) components of the average velocity *

*The longitudinal component of average particle velocity $u_{\alpha\varphi}$ in the case of a closed torus is equal to zero.

$$
\left.\begin{aligned}
\mathbf{u}_{at} &= \mathbf{u}_{ad} + \mathbf{u}_{a\perp},\\
\mathbf{u}_{ad} &= \frac{c\,[\mathbf{E}\times\mathbf{H}]}{H^2\left(1+\frac{\nu_a^2}{\omega_a^2}\right)} - \frac{cT_a\,[\nabla n_a\times\mathbf{H}]}{Z_a e n_a H^2\left(1+\frac{\nu_a^2}{\omega_a^2}\right)},\\
\mathbf{u}_{a\perp} &= \frac{Z_a e \nu_a \mathbf{E}_t}{m_a(\nu_a^2+\omega_a^2)} - \frac{\nu_a T_a \nabla_t n_a}{m_a n_a(\omega_a^2+\nu_a^2)},
\end{aligned}\right\} \qquad (8)
$$

in which $\omega_a = \frac{eH}{m_a c}$ - Larmor frequency; index t indicates the transverse vector components.

The vector $\mathbf{u}_{ad}$ represents the velocity of particle drift conserved in the absence of collisions. Let us note that the drift produced by the nonuniform magnetic field is implicitly given by the second in the expression for $\mathbf{u}_{ad}$ [see (9)]. Vector $\mathbf{u}_{a}$ represents the velocity of particle movement along the electrical field and the concentration gradient connected with the collisions.

Taking into consideration (1) and (2), we may easily obtain by employing (8) the following expression for the divergence in particle flow

$$
\left.\begin{aligned}
\nabla(n_a\mathbf{u}_a) &= \frac{1}{r}\frac{\partial}{\partial r}(r n_a u_{ar}) + \frac{\partial}{\partial z}(n_a u_{az}) \approx -\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{rcn_a E_z}{H\left(1+\frac{\nu_a^2}{\omega_a^2}\right)}\right] +\\
&+ \frac{Z_a e\nu_a}{m_a}\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{rn_a E_r}{(\omega_a^2+\nu_a^2)}\right] - \frac{T_a\nu_a}{m_a}\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{r}{(\omega_a^2+\nu_a^2)}\frac{\partial n_a}{\partial r}\right] +\\
&+ \frac{c}{H\left(1+\frac{\nu_a^2}{\omega_a^2}\right)}\frac{\partial(n_a E_r)}{\partial z} + \frac{Z_a e\nu_a}{m_a(\omega_a^2+\nu_a^2)}\frac{\partial(n_a E_z)}{\partial z} -\\
&- \frac{T_a\nu_a}{m_a(\omega_a^2+\nu_a^2)}\frac{\partial^2 n_a}{\partial z^2} + \frac{2cT_a}{Z_a eRH\left(1+\frac{\nu_a^2}{\omega_a^2}\right)^2}\frac{\partial n_a}{\partial z}.
\end{aligned}\right\} \qquad (9)
$$

The last term defines the change in concentration due to the drift caused by the nonuniform magnetic field.

In order to state expression (8) for flow divergence more precisely, we must calculate the intensity of the electrical field in the plasma from quasineutrality conditions (4) and (5). We will keep in mind in our calculations that the following inequalities are satisfied for the experimental conditions discussed below

$$\omega_e \gg \nu_e; \quad \omega_e\omega_i \gg \nu_e\nu_i \tag{10}$$

(the first inequality being a corollary of the second).

Let us observe that in the case of plasma decay within a straight cylinder of great length (when $R \to \infty$), the quasineutrality condition (5) may be satisfied if the components of electron and ion velocity in the direction of the gradient of concentration are the same ($u_{e\perp} = u_{i\perp}$) . In this instance we obtain a regime of ambipolar diffusion. While maintaining inequality (10), the rate of diffusion yields the relationship (see, for example, [2])

$$\mathbf{u}_D = -D_\perp \frac{\nabla_t n}{n}; \quad D_\perp = \frac{(T_e + T_i)\nu_e}{m_e \omega_e^2}. \tag{11}$$

The electrical field insuring the quasineutrality of the plasma is calculated employing the following inequality

$$\mathbf{E}_D = \frac{T_i \nabla_t n}{en}. \tag{12}$$

The electrical field within the toroidal chamber differs, of course, from (12). We will look for it in the form

$$\mathbf{E} = \mathbf{E}_D + \mathbf{E}_R. \tag{13}$$

Employing (12) and (13) and equating the divergences in the flow of electrons and ions (5), (9), we obtain the following equation after simple transformations

$$\frac{1}{r}\frac{\partial}{\partial r}\left\{\frac{rc\nu_i^2 n E_{Rz}}{H(\omega_i^2 + \nu_i^2)} + \frac{re\nu_i n E_{Rr}}{m_i(\omega_i^2 + \nu_i^2)}\right\} + \frac{\partial}{\partial z}\left\{-\frac{c\nu_i^2 n E_{Rr}}{H(\omega_i^2 + \nu_i^2)} + \right.$$
$$\left. + \frac{e\nu_i n E_{Rz}}{m_i(\omega_i^2 + \nu_i^2)} + \frac{2cn(T_e + T_i)}{eRH}\right\} = 0 \tag{14}$$

[inequalities (2) and (10) here taken into consideration].

We may calculate the components of the electrical field separately by setting the brackets under the derivative sign equal to zero

$$\left.\begin{aligned} E_{Rr} &= \frac{2(T_e + T_i)}{eR}; \quad E_{Rz} = -\frac{2(T_e + T_i)\omega_i}{eR\nu_i}; \\ \mathbf{E} &= \mathbf{E}_D + \mathbf{E}_R = \frac{T_i}{e}\frac{\nabla_t n}{n} - \frac{2(T_e + T_i)}{e}\frac{\nabla H}{H} - \frac{2\omega_i(T_e + T_i)}{e\nu_i}\frac{[\mathbf{H} \times \nabla \mathbf{H}]}{H^2}. \end{aligned}\right\} \tag{15}$$

It should be observed that the distribution of the space charge field calculated in this manner satisfies not only equation (14), but also the condition of the equality of electron and ion flows at any point along the boundary of the plasma (at 0 boundary concentration). This condition is obviously necessary in the case of dielectric chamber walls. It is possible that the field distribution in (15) is not the only one satisfying equation (14).

Substituting (15) in expression (9) for $\nabla(n_e\mathbf{u}_e)$ and keeping (2) and (10) in mind, we obtain the following relationship

$$\nabla(n\mathbf{u}_e)=\nabla(n\mathbf{u}_i)=-D_\perp\Delta_\perp n+w\frac{\partial n}{\partial r}, \tag{16}$$

in which are introduced the designations

$$\Delta_\perp n=\frac{\partial^2 n}{\partial r}+\frac{\partial^2 n}{\partial z^2}, \tag{17}$$

$$w=\frac{2D_\parallel}{R} \tag{18}$$

--rate of toroidal plasma drift,

$$D_\parallel=\frac{(T_e+T_i)}{m_i\nu_i} \tag{19}$$

--coefficient of ambipolar diffusion in the absence of the magnetic field (or along the field).

The equation for plasma decay (3) thus takes the form

$$\frac{\partial n}{\partial t}-D_\perp\Delta_\perp n+w\frac{\partial n}{\partial r}=0. \tag{20}$$

b) Integrating the Decay Equation

Assuming concentration on the plasma boundary (on the surface of the toroidal chamber) is equal to zero, let us now find the solution to the equation for plasma decay (20). The general solution to the equation may be presented in the form

$$n=\sum_k c_k e^{-\frac{t}{\tau_k}} s_k(r,z)e^{\frac{w}{2D_\perp}r}, \tag{21}$$

where

$$\frac{1}{\tau_k}=\frac{D_\perp}{\Lambda_k^2}+\frac{w^2}{4D_\perp}, \tag{22}$$

s_k - eigenfunctions of the equation

$$\Delta_{\perp} s + \frac{1}{\Lambda^2} s = 0, \tag{23}$$

satisfying the zero boundary conditions; Λ_k - the corresponding eigenvalues; c_k - constant coefficients designating the initial distribution of concentration.

After the passage of a sufficient period of time following the beginning of plasma decay $t \gg \frac{\Lambda_0^2}{D_\perp}$ only the first term in sum (21), corresponding to the greatest value $\Lambda = \Lambda_0$, proves to be of substance

$$n = c_0 e^{-\frac{t}{\tau}} s_0(r, z) e^{\frac{w}{2D_\perp} r}. \tag{24}$$

Plasma decay in this stage proves to be exponential. In accordance with (22), the inverse constant of decay may be written in the form of the sum of the term defining the rate of diffusion elimination of the particles (unconnected with the curvature of the chamber) and the term appearing as a result of toroidal drift

$$\left.\begin{aligned} \frac{1}{\tau} &= \frac{D_\perp}{\Lambda_0^2} + \frac{1}{4}\frac{w^2}{D_\perp} = \frac{1}{2\tau_m}\left(\frac{D_\perp}{D_0} + \frac{D_0}{D_\perp}\right), \\ \frac{1}{\tau_m} &= \frac{w}{\Lambda_0} = \frac{2D_\parallel}{R\Lambda_0}, \ D_0 = \frac{w\Lambda_0}{2} = \frac{D_\parallel \Lambda_0}{R}. \end{aligned}\right\} \tag{25}$$

As can be seen from (25), with a monotonic change in $D_\perp$, the time constant passes through its maximum τ_m when the coefficient of transverse diffusion equal to D_0.

The function $s_0(r, z)$ entering into (24) defines in accordance with (23) what is referred to as the "diffusion" distribution of concentrations over a cross section of the chamber. We obtain this distribution with the "rectification" of the toroidal chamber (when R $\to \infty$). In the case of a toroidal chamber with a finite radius of curvature, the distribution maximum appears in a position shifted farther in the direction of the drift [the exponential factor in (24)] the greater is the ratio of the rate of drift to the coefficient of lateral diffusion.

The concentration distribution in the initial stage of plasma decay may differ from (24). In this instance, the rate of the elimination of charged plasma particles may be either higher or lower than at the end of the decay process.

We should point out that the drift of the charged particles toward the chamber walls occurs as a result of lateral diffusion alone and is determined entirely by the concentration gradient. The particle flow connected with the drift nw in fact vanishes near the walls, since the concentration vanishes as well. If the initial distribution of concentrations is symmetrical (near diffusion [concentration--TR]), the rate of particle drift toward the walls therefore proves to be identical to that which occurs in the absence of toroidal drift. In consequence of the drift there then occur a shift in the distribution maximum and increases in both the rate of plasma diffusion and the concentration gradient near the chamber walls, toward which the drift is occurring. Practically exponential decay with the time constant calculated in accordance with equality (25) must be established over a period of time of the order of the "drift time" $\left(\frac{l_{\perp}}{w}\right)$.

c) Comparing Theoretical with Experimental Results

Comparison of theoretical conclusions with the experimental results obtained by Bostick and Levine [1] shows a good correspondence between them. The maximum for the curve defining the relationship between the plasma decay constant and the magnetic field $\tau(H)$ observed in work [1] probably corresponds to the maximum following from relationship (25).

The maximum value of the decay constant τ_m, calculated on the basis of the experimental data, increases with pressure, which also agrees with the formula in (25). We should point out that there is a substantial quantitative discrepancy in value τ_m. The value determined experimentally proves to be 1.5-2.5 times smaller than the value as calculated.

Quantitative agreement between the conclusions drawn from the theory developed above and the experimental data of Bostick and Levine was hardly to be anticipated. These experiments were conducted within a metal chamber. Equalizing the potential on the boundaries of the plasma should lead to a change in the space-charge field calculated in accordance with relationships (15) for any case near the boundaries. The comparatively large curvature of the toroidal chamber employed in the experiments could be another cause of discrepancies. The toroid's radius of curvature was altogether 2.5 times greater than the width of the rectangular cross section, and the low toroidality condition (2) was not satisfied. Discrepancies between the experiment and the theory may also have been connected with deficiencies in the procedure used in work [1] to measure concentration. The superhigh-frequency measuring field employed in the experiments could cause string plasma disturbances, since the measurments were conducted at frequencies near that of electronic cyclotron resonance.

In order to test the theory quantitatively, we undertook an experimental study of plasma decay within a dielectric toroidal chamber with a radius of curvature much greater than its transverse dimensions.

2. THE METHOD OF THE EXPERIMENTAL STUDY

The experimental study of plasma was conducted in quartz chambers, circular in cross section, with an internal diameter of a = 0.6 cm. Cylindrical chambers 40 cm in length d (Figure 2,a) were employed in measurements within the uniform and "corrugated" magnetic field (Sect. 3). For measurements within the toroidal magnetic field (Sect. 4), we used cylindrical chambers 60 cm in length d bent in the form of a circular arc with a radius R of 28 cm, that is, chambers representing part of a torus (Figure 2,b). At the ends of the discharge chambers were hot tungsten cathodes and anodes.

A magnetic field intensity of up to 2600 Oe was created using a solenoid consisting of individual coils. Magnetic field nonuniformity along the length of the chamber (along its axis) did not exceed 6%. The chambers were centered relative to the solenoid using a special guide tube and spacers.

Prior to the measurements, the experimental chambers were filled with spectrally pure helium (pressure p = 0.02 - 1 mm Hg). The chambers were evacuated over a period of 40-50 hr and heated at a temperature of 400-450°C with forced heat. The chambers were then discharge-treated and filled. The pressure of the gases remaining in the system detached from the pumps was not greater than 10^{-7} mm Hg. Filling the chambers was accomplished in a number of experiments with the use of special ampules of spectrally pure gas placed in the discharge chambers prior to evacuation. During the measuring procedure, the gas pressure was monitored with the use of a thermocouple manometer whose graduation was preliminarily checked using a McLeod manometer.

Plasma was created within the chamber by means of high-voltage pulses 2μs in duration and at a repetition frequency of 30 Hz. Discharge current for the duration of the pulse amounted to 0.5-1 A.

The concentration of charged plasma particles was then measured during the period between discharge pulses. Measurements were performed employing the resonator method (see [3], for example). We placed a cylindrical resonator (internal diameter a_1=2 cm, length--1.8 cm) with apertures in the ends corresponding to the size of the chamber (Figure 2) over the chamber with the plasma. The resonator was designed to generate TM_{010} oscillations within the 3-centimeter wave range. In the case of this type of oscillation, the electrical field runs parallel with the axis of the resonator. The loaded Q-factor for the resonator with the quartz chamber was 1500-2000. The connection between the shift in resonator resonance frequency Δf, caused by the introduction of the plasma into the resonator and the average concentration of electrons with respect to cross section $\bar{n}$ is given by the relationship [3]

$$\frac{\Delta f}{f} = \frac{1}{2} A_{\gamma} \frac{n}{n_{\text{кр.}}}; \quad n_{\text{кр.}} = \frac{\pi m_e f^2}{e^2}, \qquad (26)$$

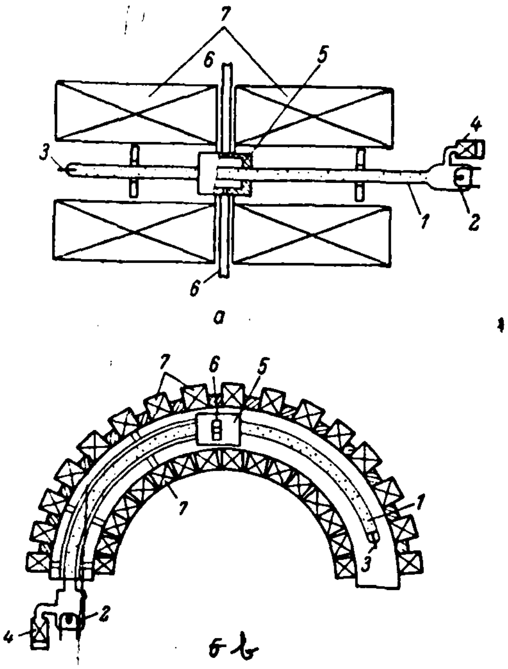

Figure 2. 1 - discharge chamber; 2 - cathode; 3 - anode; 4 - manometric bulb; 5 - measuring resonator; 6 - input and output waveguides; 7 - solenoid coil.

where f - field frequency; A_v - coefficient of the form, the value of which is calculated with the following approximated relationship with the selected dimensions

$$A_v \approx 3.7 \frac{a^2}{a_1^2} \approx 0.33. \quad (27)$$

We should point out that the relationship between frequency shift and electron concentration does not depend on a constant magnetic field, since the high-frequency electrical field is parallel to the magnetic field. The effect of the magnetic field on the measurements of concentration could therefore by caused only by resonator distortions. The effect here was not a substantial one, however, since the measurements were performed at frequencies far from the frequency of electronic cyclotron resonance (in contrast with the experiments in work [1]).

The procedure employed in measuring the frequency shift in the case of the resonator with the plasma was analogous to that employed in work [4], and we will not devote any time to it. A block diagram of the experimental apparatus employed is shown in Figure 3. The accuracy of frequency shift measurements was 0.2 MHz. The minimum measurable concentration was, accordingly, in the neighborhood of $2 \cdot 10^8$ 1/cm^3.

3. RESULTS OF A STUDY OF PLASMA DECAY IN A UNIFORM AND CORRUGATED MAGNETIC FIELD

Before studying the effect of toroidal nonuniformity in the magnetic field on plasma decay, we felt that we should first undertake a study of plasma decay within a uniform magnetic field. To conduct these experiments we employed straight cylindrical chambers (Figure 2,a) filled with helium at a pressure of 0.04-0.4 mm Hg.

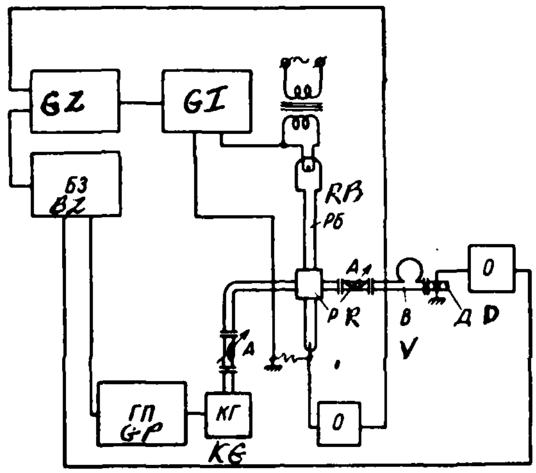

Figure 3. GZ - activating pulse generator; GI - high-voltage pulse generator; BZ - delay unit; GP - sawtooth voltage generator; KG - klystron generator; O - oscillograph; RB - discharge chamber; R - resonator; A - attenuator; V - wave meter; D - detector section.

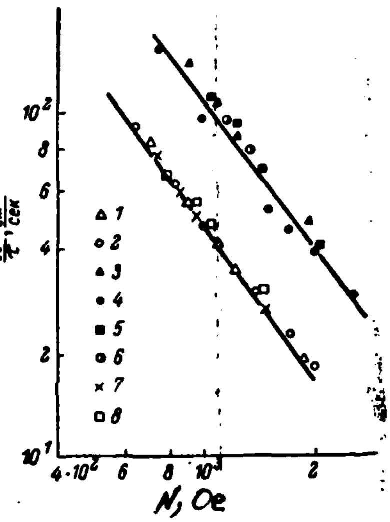

Figure 4. a) $\frac{\Lambda_0^2}{\tau} = f(H)$ - uniform magnetic field ($\delta < 6\%$), $p = 0.04-0.05$ Hg. 1 - data from the present study; 2 - data from work [6], p = 0.35--0.4 mm Hg; 3 - data from the present study; 4 - data from work [6]; b) p = 0.4 mm Hg

$\frac{\Lambda_0^2}{\tau} = f(H_{max})$. $5 - \delta = \frac{2(H_{max} - H_{min})}{(H_{max} + H_{min})} = 30\%$; $6 - \delta = 50\%$. a) $p = 0.04-0.05$ mm Hg. $\frac{\Lambda_0^2}{\tau} = f(H_{min})$; $7 - \delta = 20\%$; $8 - \delta = 30\%$.

In the case of charged plasma particle concentrations* lower than $5 \cdot 10^9 - 10^{10}$ cm^{-3}, the change in concentration over time proved to be

*We refer here as well as below to average plasma concentration with respect to the cross section of the chamber.

exponential. This is evidence of the fact that at these concentrations only a small role is played by nonlinear processes, that is, by the diffusion connected with electron-ion collisions and the recombination (see [5]). The time constant of plasma decay was calculated on the basis of the slope of the curves describing the dependence of the logarithm of concentration on time

$$\frac{1}{\tau} = -\frac{d(\ln n)}{dt}. \qquad (28)$$

Figure 4 presents the results of the calculation of τ. Plotted along the abscissa is the value $\frac{\Lambda_0^2}{\tau}$ (for a cylindrical chamber $\Lambda_0 \approx \frac{a}{4.8}$), which in the case of the diffusion mechanism of decay should be equal to the coefficient of lateral diffusion. As we can see from Figure 4, the results from our calculation of the value of Λ_0^2/τ in the present work are in good agreement with the results presented in work [6]. The values of the coefficient of lateral diffusion $\left(D_{\perp} = \frac{\Lambda_0^2}{\tau}\right)$ prove to be significantly greater than the theoretical values (for greater detail, see [6]).

We also tested for the impact on plasma decay of a longitudinal "corrugated" nonuniform magnetic field. This test was undertaken in connection with the fact that there was considerable longitudinal nonuniformity (this nonuniformity reached 6%, as indicated above) in the solenoid comprising individual coils. The solenoid coils were combined into two groups in order to create a controlled longitudinal nonuniformity in the magnetic field. The current through each group of coils was varied independently. The spatial period of the nonuniform field (along its axis) was equal to $h \approx 10$ cm. During the measuring process the cavity resonator, which was used to determine the concentration of charged plasma particles, was located in the area of the maximum magnetic field. The results of measurements of the decay constant within a range of concentrations of $2 \cdot 10^8 - 5 \cdot 10^9$ cm^{-3} are presented in Figure 4.

At a helium pressure of ≈ 0.4 mm Hg, the time of longitudinal ambipolar diffusion over a length equal to the spatial period of the nonuniformity is substantially greater than the time of lateral diffusion

$$\frac{h^2}{D_{\parallel}\pi^2} \gg \frac{\Lambda_0^2}{D_{\perp}} \qquad (29)$$

(in estimation we assumed $D_{\parallel} = 1400$ cm^2/s in accordance with [7]; we estimated $D_{\perp}$ on the basis of the experimental data). The rate of diffusion had therefore to be calculated by the magnetic field at the point where the measuring resonator was located ($H=H_{max}$).

The relationship between $\frac{\Lambda_0^2}{\tau}$ and H_{max} for this pressure is accordingly presented in Figure 4. As was to be anticipated, in the case of a different degree of nonuniformity, this relationship proved to be identical to the one established in the case of the uniform magnetic field.

If longitudinal diffusion occurs much more rapidly than lateral [if, that is, the inequality the inverse of (29) is observed], longitudinal diffusion in the region of the minimum magnetic field with subsequent lateral diffusion is the shortest "path of diffusion" from out of the region of the maximum magnetic field. Diffusion time should accordingly be near the time of lateral diffusion in the case of a magnetic field equal to the minimum. The conditions of the experiments performed at a helium pressure of 0.04-0.05 mm Hg approach this case. As we can see from Figure 4, the relationship between $\frac{\Lambda_0^2}{\tau}$ and H_{min} in the case of the nonuniform magnetic field at this pressure is found to be the same as that occurring in the case of the uniform field.

The results presented indicate that plasma decay time in a magnetic field with longitudinal nonuniformity is found to be the interval between the times of lateral diffusion with the maximum and minimum magnetic field.

4. RESULTS OF A STUDY OF PLASMA DECAY IN A TOROIDAL MAGNETIC FIELD

The discharge chambers shown in Figure 2,b were used to study plasma decay within a toroidal magnetic field. The chambers were filled with helium at a pressure of 0.02-0.9 mm Hg.

Measurements indicated that under certain conditions (at pressures of 0.05-0.5 mm Hg and with magnetic fields greater than 1000-2000 Oe), the change over time in charged particle concentration differs from the exponential within the range of values $2 \cdot 10^8 - 10^{10}$ cm^{-3}, in which nonlinear processes are unimportant. A distinct discontinuity was observed in this regard on the curves describing the relationship between $\ln \bar{n}$ and t. Characteristic curves of this type are shown in Figure 5. In all cases in which a discontinuity was observed, the value of the decay constant, as calculated with respect to the slope of the curves in the initial region (at concentrations of $2 \cdot 10^9 - 10^{10}$ $1/cm^3$), was close to that of the decay constant within the uniform magnetic field (in straight chambers). Results from the calculation of the plasma decay constant with respect to the slope of the curves $\ln n = f(t)$ at the termination of decay (with concentrations lower than 10^9 cm^{-3}) are presented in Figure 6. The relationship between $\frac{1}{\tau}$ and H has a characteristic minimum. It was possible to observe this minimum with magnetic fields weaker than 2600 Oe for helium pressures lower than 0.15 mm Hg. At a helium pressure of 0.4 mm Hg we observe only a limited slowing down in the drop of curves $\frac{1}{\tau}(H)$ as compared with the curves obtained for the uniform magnetic field (in the straight chamber). At a pressure of 0.9 mm Hg, the relationship between τ and H is found to be virtually the same as that established for the uniform field.

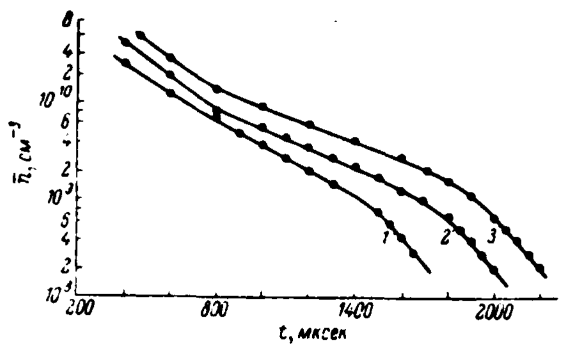

Figure 5

$p = 0.055$ мм Hg   1 — H = 1600, 2 — 1900, 3 — 2600 Oe

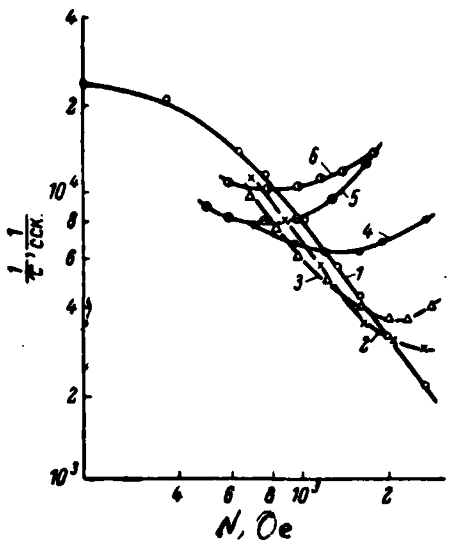

Figure 6

1 — $p = 0.9$, 2 — 0.4, 3 — 0.12, 4 — 0.055, 5 — 0.04, 6 — 0.025 мм Hg

Let us now compare the experimental data with the results obtained from theoretical analysis. Let us note first of all that under the conditions prevailing in the experiments which were performed, longitudinal diffusion occurs much more slowly than lateral diffusion $\left(\frac{D_\parallel \pi^2}{d^2} \ll \frac{D_\perp}{\Lambda_0^2}\right)$. The characteristics of plasma decay in the chamber representing part of a torus (Figure 2,b) should accordingly be identical to those in a closed torus.

The shape of the curves of plasma decay similar to those shown in Figure 5 may be easily explained if we assume that at the beginning of the decay process, the distribution of concentration over the cross section of the chamber is symmetrical and close to the diffusion [concentration--TR]. This would appear to be a plausible assumption, since the nonlinear processes of removing the charged particles, which at the onset of decay may be more effective than toroidal drift, lead to a "symmetrization" of the distribution of concentrations. In the case of a symmetrical distribution, the rate of plasma decay should, according to the theory, be identical with that in the uniform magnetic field (p. 1047). This is precisely what is to be observed in the experiment. Only after a time equal to several "drift times" should we be able to establish the nonsymmetrical distribution of concentrations characteristic of the toroidal chamber (24).

Let us now compare relationship (25), which defines the constant of plasma decay after the distribution of concentrations has been established, with the experimental results shown in Figure 5. We should keep in mind that in the experiment, the value of the coefficient of lateral diffusion in the uniform magnetic field is

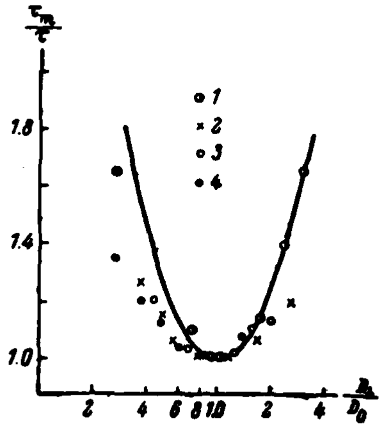

Рис. 7.

Figure 7. Experimental data: 1 - p = 0.12; 2 - 0.055; 3 - 0.04; 4 - 0.025 mm Hg; Solid line represents theoretical curve.

found to be substantially greater than that arrived at theoretically (see p. 1051 and [6]). In making our comparison, therefore, we will substitute in (25) the experimentally calculated values of the coefficient of lateral diffusion.*

In the accompanying table we compare the experimental and theoretical values of the maximum decay constant and the corresponding values of the coefficient of lateral diffusion. The theoretical values τ_m and D_0 are calculated in accordance with the formula in (25). In accordance with the data presented in [7], we have assumed the value of the coefficient of longitudinal diffusion here to be equal to $D_{\parallel} = 540/p$ cm^2/s (p in mm Hg). Experimental

1 p, мм рт. ст.	2 τ_m, мксек.		5 D_0, см^2/сек.	
	3 экспериментальные значения	4 теоретические значения	3 экспериментальные значения	4 теоретические значения
0.025	100	80	70	95
0.04	130	130	70	60
0.055	160	180	35	43
0.12	280	380	20	20
0.4	> 400	1300	< 30	6

Key to Table: 1 - mm Hg; 2 - μs; 3 - experimental values; 4 - theoretical values; 5 - cm^2/s.

values of τ_m were calculated using the curves in Figure 6. The value of the magnetic field with which the decay constant is maximum was calculated on the basis of these curves as well. The connection between the magnetic field and the coefficient of lateral diffusion was established on the basis of the results of measurements performed in the uniform magnetic field.

We can see from the table that at a helium pressure of 0.02-0.12 mm Hg, the experimental and theoretical values τ_m, D_0 are in good agreement with one another. The case in which at pressures of 0.4 and 0.9 mm Hg a minimum on curves $\frac{1}{\tau}(H)$ was not observed (with $H < 2600$ Oe) is also in agreement with the theory.

Let us now compare the path of curves $\frac{1}{\tau}(H)$ for various pressures. Figure 7 shows the relationship between $\frac{1}{\tau}$ and $D_{\perp}$ in relative

*It is assumed in the case of this implicit example that the theoretical expression for the coefficient of lateral diffusion is correct, while deviations of the experimental values from the theoretical are connected with an abnormally high frequency of collisions.

units. This relationship is constructed by employing the curves in Figure 6 and the experimental curves describing the relationship between $D_\perp$ and H within a uniform magnetic field. The experimental data obtained at various helium pressures all fit the same curve in accordance with (25). The values of τ on the curve differ from the theoretical values by no more than a factor of 1.5.

The experiments which have been performed thus indicate that the theory set forth above correctly describes the impact of toroidal drift on plasma decay.

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